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# Fallout Computer Codes
## A Bibliographic Perspective


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This report is a summary overview of the basic features and differences among the major radioactive fallout models and computer codes that are either in current use or that form the basis for more contemporary codes and other computational tools. The DELFIC, WSEG-10, KDFOC2, SEER3, and DNAF-1 codes and the EM-1 model are addressed. The review is based only on the information that is available in the general body of literature.

This report describes the fallout process, gives an overview of each code/model, summarizes how each code/model handles the basic fallout parameters (initial cloud, particle distributions, fall mechanics, total activity and activity to dose rate conversion, and transport), cites the literature references used, and provides an annotated bibliography for other fallout code literature that was not cited.

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# CONVERSION TABLE

**Conversion factors for U.S. customary to metric (SI) units of measurement**

| To Convert From | To | Multiply |
|---|---|---|
| angstrom | meters (m) | 1.000 000 X E-10 |
| atmosphere (normal) | kilo pascal (kPa) | 1.013 25 X E+2 |
| bar | kilo pascal (kPa) | 1.000 000 X E+2 |
| barn | meter$^2$ (m$^2$) | 1.000 000 X E-28 |
| British Thermal unit (thermochemical) | joule (J) | 1.054 350 X E+3 |
| calorie (thermochemical) | joule (J) | 4.184 000 |
| cal (thermochemical)/cm$^2$ | mega joule/m$^2$(MJ/m$^2$) | 4.184 000 X E-2 |
| curie | giga becquerel (GBq)* | 3.700 000 X E+1 |
| degree (angle) | radian (rad) | 1.745 329 X E-2 |
| degree Fahrenheit | degree kelvin (K) | $t_K = (t°f + 459.67)/1.8$ |
| electron volt | joule (J) | 1.602 19 X E-19 |
| erg | joule (J) | 1.000 000 X E-7 |
| erg/second | watt (W) | 1.000 000 X E-7 |
| foot | meter (m) | 3.048 000 X E-1 |
| foot-pound-force | joule (J) | 1.355 818 |
| gallon (U.S. liquid) | meter$^3$ (m$^3$) | 3.785 412 X E-3 |
| inch | meter (m) | 2.540 000 X E-2 |
| jerk | joule (J) | 1.000 000 X E+9 |
| joule/kilogram (J/Kg) (radiation dose absorbed) | Gray (Gy) | 1.000 000 |
| kilotons | terajoules | 4.183 |
| kip (1000 lbf) | newton (N) | 4.448 222 X E+3 |
| kip/inch$^2$ (ksi) | kilo pascal (kPa) | 6.894 757 X E+3 |
| ktap | newton-second/m$^2$ (N-s/m$^2$) | 1.000 000 X E+2 |
| micron | meter (m) | 1.000 000 X E-6 |
| mil | meter (m) | 2.540 000 X E-5 |
| mile (international) | meter (m) | 1.609 344 X E+3 |
| ounce | kilogram (kg) | 2.834 952 X E-2 |
| pound-force (lbf avoirdupois) | newton (N) | 4.448 222 |
| pound-force inch | newton-meter (N·m) | 1.129 848 X E-1 |
| pound-force/inch | newton/meter (N/m) | 1.751 268 X E+2 |
| pound-force/foot$^2$ | kilo pascal (kPa) | 4.788 026 X E-2 |
| pound-force/inch$^2$ (psi) | kilo pascal (kPa) | 6.894 757 |
| pound-mass (lbm avoirdupois) | kilogram (kg) | 4.535 924 X E-1 |
| pound-mass-foot$^2$ (moment of inertia) | kilogram-meter$^2$ (kg·m$^2$) | 4.214 011 X E-2 |
| pound-mass/foot$^3$ | kilogram/meter$^3$ (kg/m$^3$) | 1.601 846 X E+1 |
| rad (radiation dose absorbed) | Gray (Gy)** | 1.000 000 X E-2 |
| roentgen | coulomb/kilogram (C/kg) | 2.579 760 X E-4 |
| shake | second (s) | 1.000 000 X E-8 |
| slug | kilogram (kg) | 1.459 390 X E+1 |
| torr (mm Hg, 0°C) | kilo pascal (kPa) | 1.333 22 X E-1 |

*The becquerel (Bq) is the SI unit of radioactivity: Bp = 1 event/s.

**The Gray (Gy) is the SI unit of absorbed radiation.

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# SECTION 1
# INTRODUCTION

The genesis of this report was requests made of DASIAC concerning some of the fallout models (and computer codes derived from these models) used by the defense community. The models and codes considered here are those that the literature indicates may be in current use by organizations other than their originators, and most were developed under DNA sponsorship. They include the DELFIC, WSEG-10, KDFOC2, SEER3, and DNAF-1 codes and EM-1. Some of these have been adapted for use in other codes and computational tools whose names are more contemporary, e.g., the FAB, CIVIC, and SIDAC codes and DNA's Fallout and Nuclear Weapon Effects Computational Aids.

The DASIAC information requests frequently concerned details of the models and were often questions related to the underlying assumptions used by the models, and occasionally how these assumptions differed from model to model. Surprise was usually evidenced at the variations in output observed after identical input data with the different predictor systems. These variations result from two major causes: first, differences in scientific opinion concerning the fallout process result in different codes using different scientific principals for some aspects of this process; second, the codes have different ways of using and manipulating information. The initial intent of this review was to both anticipate and summarize these inquiries; to evaluate the models and find the original references to each of the underlying model assumptions and, if possible, how these assumptions relate to measured data. For example, some models assign a fixed fraction of total radioactivity to the stem of a rising mushroom cloud and the remainder to the main cloud. What was the origin of this partition fraction? What was the database for this estimate? Few sensitivity studies have been performed on the effects of changes in these parameters. However it was soon apparent that this could not be done using the published documents, since the information relating to the source of many of the parameters is not available in the documents, and the resources available precluded a more in-depth study. Since the intent of this report was to provide background information to DASIAC patrons requesting fallout code information, two options were then considered. The first was to prepare an annotated bibliography on each code that would allow the user with need of code information to quickly identify those documents most appropriate to the user's need. The second option was to prepare an evaluation of how the algorithms in each code handled the parameters that define the fallout process; this option would give potential code users the tools to determine for themselves the underlying assumptions and perhaps to more easily evaluate how various code parts replicated reality. The second option seemed to fulfill the DASIAC objective best, and would be of greatest benefit to the DASIAC user, but a thorough appraisal of all the current computer codes would require evaluation of the source code listings and again would be too large an effort for the resources available. Therefore, this report is a compromise; it gives summary descriptions of each of the codes/models, describes the original source of some of the underlying assumptions and, when information is available in the literature, indicates how each code calculates the various model elements. Lastly, the appendix presents annotated bibliographic references to codes not covered in this review, either because they are older or are not in general use.

There is a *caveat.* Codes that are designed to study a phenomena, like fallout, are never complete. A major barrier to comprehension stems from a misconception as to how a scientific code works. Potential users often have in mind something like a spread sheet or word processing program for their office computer, and they equate this to a scientific code. The difference is not the complexity, indeed some of these home and office programs are extremely complex, but is rather how they are used. When a program is selected for home or office use, the various features of similar programs are evaluated, the selection made, then the idiosyncrasies of the program learned. The program itself is almost never modified by the individual user; the program is complete and finished when sold. In contrast, a scientific code is never finished. The originator adds and changes various sections as new knowledge about the subject is learned. Users may also make changes reflecting new knowledge, but the user is normally not able to constantly keep abreast of the latest scientific advances. The user may also make modifications to those parts of the code that have a major effect on a specific need, and tailor the code accordingly. Thus, codes carrying the same name and originally from the same developer may contain both subtle and sometimes profound differences. A prime example is the SEER series of codes, where numerous versions have been designed, each for a specific need. Also, one user may pass the code to another without fully documenting the modifications made, which can lead to confusion when codes are compared. Some DNA sponsored codes, notably those relating to electromagnetic propagation in a nuclear environment, use a single contractor to insure the code is always up to date. The contractor may make the modifications required by the end user and all users are required to use the latest version of the code. This was originally done with the DELFIC fallout code. Periodic user meetings have been held to inform users of new changes and to plan for future versions of the code, but this is not currently done for any fallout code. This extra attention may be justified for codes that may be used in the design and procurement of systems needed to insure wartime communications or to direct missile destroying activities but not for fallout codes where the major concern is more long term rather than the immediate design and procurement of some weapon system.

In the sections that follow, first the fallout process, emphasizing the elements modeled, is briefly described. Next is a short description of each code illustrating the major differences between them. Then a listing of the important elements that are modeled by the codes and, when information is available in the code reports, an examination of how the codes calculate these elements.

# SECTION 2
# THE FALLOUT PROCESS

Many physical phenomena are associated with a nuclear detonation. These are related to, and are a function of, many factors. The inclusion here of a brief discussion of the factors that are presently considered to play major roles in the determination of the mechanics and the characteristics of fallout is necessary to understand differences among the various codes.

At the time of detonation, enormous amounts of energy are released in the form of heat and ionizing radiation. Everything in the nuclear weapon and the immediate surroundings is vaporized at extremely high temperatures and a rapidly expanding fireball is formed. Except for deeply buried bursts, this fireball rushes upwards, cooling first by radiation and then by expansion and entrainment of air and soil or water. The rising fireball creates a strong, turbulent updraft. The center of the fireball is hottest so it rises fastest, quickly developing strong internal revolving air currents that convert the rising bubble into a toroid. During this rise, large volumes of soil, for a surface or near surface burst, are drawn into the fireball. This forms a rapidly rising stem, containing tons of soil and debris from beneath the fireball. Much of the material in the stem may be circulated through and around the toroidal-shaped fireball or perhaps even be sucked into the fireball itself. At first the temperature will be high enough to vaporize this soil, but as the fireball cools the temperature will quickly drop to the point where the soil grains will only be melted on the surface, then to a point where no melting occurs. Depending on the height of burst above the ground surface and weapon design, a portion of this lofted material may contain some neutron induced radioactivity.

The vapors inside the fireball are intensely radioactive. This radioactivity comes from three sources, fragments of fissionable matter, unfissioned matter, and bomb case debris and surrounding material that have been made radioactive by absorbing the neutrons released during the detonation. The composition of the fission products varies somewhat with both the fissionable material and the weapon design. About 1,200 different nuclides of 36 elements are represented. Most are radioactive and decay into a chain, or sequence, of daughter products that are also radioactive until the decay reaches a stable isotope. As the fireball cools, condensation of the vapors into solid particles that grow as more material is added to their surfaces begins. How large the particles grow depends in part on the density of the fireball. An airburst, where the fireball never reaches the ground and therefore involves nothing condensable except the weapon itself, will produce particles only a few tenths of a micron in diameter. If the fireball touches the ground, as in a surface burst, it will vaporize some of the soil and produce particles hundreds and thousands of times larger. Also, soil entrained by the rising fireball will be available to receive a radioactive coating.

Particle formation proceeds in the order of the boiling points of the materials present in the fireball–those having higher boiling points, like iron, condensing first and those having lower boiling points remaining in a gaseous state until later. Only about 55 grams of fission products are produced per kiloton of fission yield, these also condense as a function of their boiling points, but since such small quantities are involved, they probably condense for the most part on or within other particles that exist in greater abundance. The fission product isotopes diffuse into smaller molten particles of the material lofted and condense on the surface of larger particles. This suggests that the large particles found near ground zero (GZ) contain disproportionate quantities of isotopes whose decay chains produce refractory[1] precursor oxides at the time in fireball history when particle formation was in progress, while the small particles found further downwind are enriched in those isotopes whose decay chains produce more volatile precursor oxides during particle formation. This phenomena, termed fractionation, affects the average energy level of different particle sizes and should be included in calculations of radioactive exposure and dose. Fractionation also involves fission products, such as the noble gasses krypton and xenon, that do not become attached to particles until they have decayed to more reactive kinds of atoms, by which time many or even most of the larger particles have already fallen out. The result is a depletion of the decay products of these gases in local fallout and a corresponding enrichment of the decay products in the small particles that tend to remain aloft longer and be deposited at greater distances.

The size, height, and geometry of the radioactive cloud is a function of yield and atmospheric conditions. The cloud rises to an altitude where the density of the gases is the same as that of the surrounding atmosphere, and the familiar mushroom-capped cloud with a long stem of dust is observed. Wind shearing may distort the symmetry of the cloud at any level. When the cloud stops rising from its own buoyancy, it is termed "stabilized". For detonations less than a few tens of kilotons, both the main cloud (or "cap") and the stem are highly radioactive. For megaton detonations, the main cloud carries most of the radioactivity. The stabilized cloud is transported through space by the winds aloft. These winds do not blow at constant speed and direction, but rather they vary by altitude, time, and geographic location. From any cloud, the largest and heaviest particles fall first (indeed some fall prior to cloud stabilization) followed by the smaller particles. For a given set of conditions, the smallest fallout particles rise highest and stay aloft the longest. The winds will determine how far and in what direction they will travel in that time. Most of the particles from an airburst are so small that they will stay aloft for days to months; hence the local fallout from such a burst is quite small. The fallout from a surface or shallow buried burst is different however. Many of its particles are large enough to return to earth within a few hours, thus they are concentrated in a smaller area and the resulting radiation exposure may be intense. The fallout-safe height-of-burst is defined as that above which no *militarily-significant* fallout will result.

Thus all of the phenomena of the detonation and the succeeding growth and rise of the fireball, cap, and stem, are grouped as being some of the more important factors that give rise to the initial distribution of radioactive particles in the air over the vicinity of GZ.

The subsequent dispersal and the ultimate pattern of fallout from the initial particle distribution around GZ is a very complex phenomena depending, among other factors, upon the particle size, the particle shape and density, and the distribution of particles as a function of height, and then the various meteorological conditions following the detonation. Owing to the heights to which the radioactive particles may rise and to the size spectrum, some particles may remain in the air for very long periods of time, their ultimate location being dependent upon various climatic and meteorological influences. Even with moderate winds, opportunity is provided for large-scale movements with or without appreciable dilution of the cloud due to turbulence. Thus, large areas on the ground may be severely contaminated with probable variations of large magnitude resulting from localized weather conditions and topography.

The preceding paragraphs indicate the numerous and complex processes, physical and chemical, that occur simultaneously throughout the fireball and cloud development, and during the transport and deposition of nuclear detonation produced radiation fields. Models and codes used to predict the fallout process are mostly concerned with the cloud geometry, the particle size and particle activity spectrum, the distribution of these particles within the cloud, the direction the winds move the particles until they reach the ground, and radioactive decay of the particles.

## SECTION 3
## FALLOUT CODES

Fallout codes may be classified in various ways. One way differentiates those that calculate from first principal physical processes from those that use either computational or graphical algorithms. Another is based on end use of the code developed information (e.g., scientific, which performs analyses of the fallout process, or operations analysis, which predicts damage assessment or strategic planning implications of a particular nuclear exchange). Codes can also be classified by functional characteristics, which indicates how they operate.

A useful functional classification is based upon the way the code handles wind effects. Two basic approaches are recognized as distinguishing among models in their predictions of fallout deposition. Some models use a single effective fallout wind (EFW) vector (these codes are often termed "smear codes"). Other models partition the cloud vertically into horizontal segments or "disks" that are acted upon by winds prevailing at the disk altitude (these codes are usually referred to as "disk throwers"). The smear codes model the initial stabilized dust cloud as a continuous distribution, or by a grouping of continuous distributions, one for each of a number of particle sizes. Each size class has an associated radioactivity. Particle fall mechanics and winds are used to track a single representative particle for each size class, beginning at the initial cloud center. As the center of each particle distribution falls and is transported by the winds, the particles associated with that size class are "smeared" across the ground. A summation over all size classes produces the ground pattern or radioactivity deposited over time. The disk thrower model also uses distinct particle size classes, but in addition the initial cloud is divided by specific altitude layers. Within each altitude layer, each particle size class is represented by a flat circular disk. Each disk has an associated activity. Particle fall mechanics and winds are used to trace a single representative particle at the center of the disk and the disk is allowed to expand by turbulent diffusion. When that particle hits the ground the entire disk is considered grounded, and the summation of all disks on the ground at a given time results in the ground pattern of radioactivity.

With either the smear or the disk thrower model, the prediction accuracy increases with an increasing number of size classes; however, more classes require more computer memory and greater computational time. All of these classifications are considered below.

## 3.1 DELFIC.

The DEfense Land Fallout Interpretative Code (References 1 through 16) is a phenomenology program developed under DNA sponsorship. It was designed for research into prediction of local nuclear fallout, and to serve as a standard against which predictions of other codes could be compared. Its calculations are designed to be exacting, avoiding shortcuts, but highly flexible. It is fairly comprehensive in its treatment of the physics of fallout transport and activity calculations. A few of the algorithms used are conjectural, but are based on the best scientific knowledge available. A major aim was to give attention to all the phenomena that are considered important in the fallout process. As a result this main frame based code is relatively slow and costly to run, and its use requires some sophistication concerning the fallout process. The code is composed of five modules covering initial conditions, cloud rise, transport, particle activity, and an output processor.

DELFIC is credited with being the main foundation element of Airrad, the fallout prediction system that has been incorporated into the DNA Fallout Computational Aid that has just been released (Reference 17). (This Aid should not be confused with the fallout module of the Nuclear Weapon Effects Computational Aid whose parentage is discussed below under the DNAF-1 code.) Since the basic documentation on Airrad is unpublished, it is not possible to discuss the extent to which Airrad uses DELFIC. What little is published in Reference 17 also credits SIMFIC, a simplified code, as a foundation element.

The initial conditions module of DELFIC begins with basic weapon and environmental parameters and provides a set of cloud properties defined at the beginning of entrainment-controlled cloud rise or approximately the time when the fireball reaches pressure equilibrium with the atmosphere. A specification of the vertical profiles of temperature, humidity, and winds is required by the model. The user may specify one of three types of fallout particle size distributions–lognormal, a power law, or an arbitrary distribution designed by the user (this latter distribution is usually one measured in a specific nuclear detonation test program). The user also selects the size-activity distribution of the particles. The mass of water, ice and dust, which are a function of ambient atmospheric conditions, and the yield and HOB, which determine the dust loading, are included in the calculations. The model will calculate fallout parameters for a contact surface burst or a pure airburst (i.e., no fireball intersect with the ground), but uses an empirical relationship for anything between.

The cloud rise module is based on an entrained buoyant bubble model that can account for the effects of the vertical atmosphere structure on the cloud rise and stabilization. The coupled differential equation calculations conserve momentum, mass, heat, and turbulent kinetic energy. Activity calculations are exact so that use of an activity normalization factor (the K-factor, i.e., the radioactive exposure rate at H+1 hour for fallout from one kiloton of fission yield spread uniformly over a unit area) is not required, and decay is modeled exactly so it is not necessary to use a gross activity decay equation such as the Way-Wigner Law.[2] Cloud properties and contents are taken to be uniform throughout the cloud volume.

### 3.2 WSEG-10.

The Weapon System Evaluation Group developed this code over 40 years ago for use in operations analysis studies, especially those involving multiple bursts in the megaton range (References 18, 19, 20, 21, and 22). Although originally designed to predict fallout from high-yield detonations, modifications have been made to lower the minimum yield to about 1 KT. In a slightly modified form it is still in use for that same purpose by the National Military Command System Support Center as a part of the Single Integrated Damage Analysis Capability (SIDAC). The model was also used as the basis for the fallout module for the hand held programmable calculator nuclear weapons effects programs by DNA (References 23 and 24).

WSEG-10 uses empirical equations to calculate fallout patterns rather than the numerical approach used by other computer codes, which makes it much faster than the numerical codes. The WSEG-10 radioactive cloud can be imagined as a floating expanding wafer that releases radioactivity at the ground surface according to a prescribed function of time, g(t). The fallout mid-line, turbulent diffusion, and wind shear expansion of the wafer are all specified by two parameters by using a wind averaging scheme from the top and bottom of the main cloud to the ground. The two parameters show the direction of the mid-line and the rate of horizontal expansion of the wafer. The expanding wafer starts at GZ with a smaller radius than other stabilized cloud models and with the activity on larger particles than those in DELFIC, which has the result of predicting the high fallout exposure rates observed near GZ for tests held in Nevada. The function g(t) represents the rate of ground deposition of radioactivity as a function of time. The model calculates g(t) by assuming that fallout descends from a nuclear cloud that is characterized initially by a Gaussian distribution in the vertical about the cloud center height of both particles and activity. The particle activity-size and fall rates were determined from a curve fit to an early fallout model developed by the RAND Corp. (Reference 25). The radioactivity in the pattern is specified for H+1 hours and incorporates the Way-Wigner (Reference 26) decay formula, $A(t) = A\, t^{-1.2}$ for times other than 1 hour. Fractionation is not considered. A K-factor, or source normalization constant is used.

The fallout isodose patterns produced are approximately elliptical and symmetric about the mid-line. The radioactivity is conserved. The code cannot handle large wind shears.

### 3.3 KDFOC2.

The K-division DNA Fallout Code was originally developed at the Lawrence Livermore National Laboratory to predict fallout from buried nuclear detonations, but it was later modified to handle surface detonations also (References 27 and 28). The code was used to predict local fallout in the SCOPE/ENUWAR study (Reference 29). The model determines, for burst time, the dimensions of the initial debris arrangement and the distribution of activity with respect to particle size and altitude. Parcels of debris follow trajectories defined by winds, turbulent diffusion, and gravitational settling. When the parcels hit the ground, their activity contributions to total exposure are summed to provide an overall fallout pattern.

The only required input specification for KDFOC2 is weapon yield. Other parameters may be specified, otherwise they are assigned default values that are for an all-fission surface contact burst with moderate-speed, low-shear winds. The code is a disk thrower with a continuous, adjustable activity-height distribution from the cloud cap to the ground. Radioactivity is mathematically conserved. The measured particle-activity sizes used are from Small Boy for surface bursts and from Schooner for buried bursts. The output is a geographic representation of the fallout pattern at the exposure levels requested and a listing of the maximum downwind distance and area of each of the closed contours.

### 3.4 SEER3.

The Stanford Research Institute originally developed the Simplified Exposure Estimate of Radioactivity for DNA to be a fast-running emulation of DELFIC that could be used in assessing fallout damage for large scale nuclear attack scenarios (References 30, 31, and 32). To accomplish this, some details were sacrificed in favor of computational speed. SEER3 is the model used by the FAS (Fallout Assessment System) and CIVIC (Civilian Vulnerability Indicator Code) codes to calculate the fallout environment. A personal computer version is available.

SEER3 is a compromise between a conventional disk thrower model and a complex curve fit to DELFIC results. Atmospheric sounding data are not used in the calculations; rather, cloud stabilization parameters from DELFIC are approximated using one of five (cloud bottom) or six (cloud top) equations appropriate to the yield range. The code gains speed by reducing the number of disks in the stabilized cloud. Because of few disks, there are times when they do not overlap after they reach the ground. In order to create smooth fallout patterns, the code creates radioactivity interstitially at the same exposure rate as at the average peak level of the nearest disks, thus radioactivity is not mathematically conserved. The activity particle-size distribution is the same for each altitude disk. SEER3 uses the mass-size distribution to distribute activity. This produces a strong bias toward large particles, and a disproportionately large portion of the fallout radioactivity is assigned to large particles that ground relatively close to ground zero. This partially compensates for the models lack of apportioning activity to the stem.

### 3.5 DNAF-1.

The Defense Nuclear Agency Fallout Code was developed by the architect of the DELFIC code to rapidly predict radioactivity from large numbers of surface bursts for use in damage assessment studies (Reference 33). Like WSEG-10 or SEER3, the model uses analytical equations rather than the numerical approach to reduce both computer time per prediction and computer storage. DNAF-1 is largely based on curve fits to DELFIC code runs, although the vertical structure of the DNAF-1 cloud differs from that of DELFIC. The model is based on a mathematical function that is fitted to activity deposition rate data derived from runs of DELFIC. The gamma radiation from dry ground-deposited fallout from both the cloud cap and the stem is considered by the model. DNAF-1 has been incorporated into the fallout module of the Nuclear Weapon Effects Computational Aid distributed by DNA (Reference 34).

### 3.6 EM-1.

The current DNA Effects Manual 1, officially known as the *Capabilities of Nuclear Weapons,* was designed to be a multi-volume compendium of current knowledge in nuclear weapons effects. Chapter 8 (Reference 35) covers radiation and fallout from surface, sub-surface, and free-air bursts over soil. Detonations on, above, or below a water surface are considered in Chapters 5 and 19 of the series. The model is not designed for computer manipulation but rather is a series of graphical techniques that can be used along with a pocket calculator to construct a fallout contour plot or calculate exposure and dose at various locations within the fallout field. Three models are presented in Chapter 8. One is based on DNAF-1, which as noted above emulates the DELFIC calculations. The model for subsurface detonations is based on a graphical scaling model developed by the U.S. Army Engineer Nuclear Cratering Group (Reference 36), other code generated data (Reference 37 and the KDFOC code), and new material. A model to predict the effects of rainout is original to EM-1.

For surface bursts, the graphs cover nine yields ranging from 0.003 KT to 100 MT, and eleven winds from 0.5 to 100 m/sec. The representation is essentially a single effective wind model and wind shear is accounted for. The stabilized cloud parameters are modeled largely by empirically fitting test data. The model assumes a straight hot line and axisymmetric contours. Two methods may be used to construct the contours. The first uses a pattern look up of one of 27 precomputed H+1 dose rate fallout patterns. The 27 patterns are a set of three wind conditions (light, medium, and strong) for each of the nine decades of yield. The second method is graphical and allows point calculations as well as construction of H+1 contours. Low-yield calculations are felt to be more accurate because the DELFIC particle size distribution used was determined from whole pattern-averaged particle data for two low-yield Nevada Test Site detonations and comparable particle size data is not available for high yield shots. If the model is used to predict fallout levels at a particular geographic location, differences of several orders of magnitude may occur. However, when used for damage assessment, gaming, or other applications involving distributed targets or probabilities, the accuracy of the fallout contours is adequate. Neither the underground burst model nor the precipitation scavenging model has been verified or tested by a quantitative study of calculational accuracy.

# SECTION 4
# MODELING OF BASIC FALLOUT PARAMETERS

The codes proceed through sequential steps to eventually produce map contours of fallout intensity. Usually these contours are related to a specific unit time after detonation, commonly H+1 hour. That is, the value shown by a particular contour is what the exposure would have been if the radioactivity that would eventually end up at that contour had all been deposited by that time. In reality, since the deposition of even close in fallout is a process that takes hours, the unit time reference activity is an artificial quantity; however, the concept is both convenient and conventional. In this section some of the important parameters used to ultimately determine the fallout contours are discussed. When possible to determine from information presented in the documents listed in the reference section, differences among the codes are noted.

## 4.1 INITIAL CLOUD.

The stabilized cloud in a smear code is modeled by either a single continuous distribution of particles in space, or by a group of continuous functions, one function for each of a series of particle classes. The classes may be divided by equal mass or equal radioactivity. Any continuous distribution function may be used to represent the distribution of activity within the cloud, and each class might be represented by a different distribution. Disk thrower codes model the initial cloud in different ways, but they all partition the cloud vertically into discrete disks that are acted upon by the winds prevailing at the disk altitude. In all models, the cloud dimensions are functions of total nuclear yield.

**DELFIC.** A disk thrower. The DELFIC dynamic cloud rise is based on the work of Huebsch (References 13, 38 and 39) modified by Norment (Reference 14). It models an ellipsoidal cloud with eccentricity of 0.75. The model accounts for the effects of atmospheric structure on cloud rise and stabilization. Radioactive particles are distributed uniformly within each vertical layer of the stabilized cloud, but each layer may carry a different amount of activity.

**KDFOC2.** A disk thrower. KDFOC2 considers the initial cloud as an inverted cone.

**WSEG-10.** In WSEG-10, the only computer-based smear code represented here, the cloud is assumed to have a normal distribution of radioactivity in the vertical. The median height is a function of the yield. The vertical dispersion is assumed to be 0.18 times the cloud center height. Norment (Reference 33) does not think that a normal vertical distribution is a good assumption for detonations less than 50 KT because much of the activity that will fall out close to GZ is initially in the cloud stem whereas the WSEG-10 Gaussian peaks at the cloud center. This has the effect of ignoring the stem radioactivity, even for low-yield detonations.

**SEER3.** A disk thrower, SEER3 (and FAS, which uses a version of the SEER code as the fallout model) models the initial cloud as an upright cylinder whose center axis is initially directly over the point of detonation. Cloud dimensions and time of stabilization are functions of total weapon yield.

**DNAF-1.** Early cloud rise is modeled after the SIMFIC code (Reference 40). Cloud rise is curve fitted to DELFIC calculations using the 1976 U.S. Standard Atmosphere profile. Stabilized cloud cap and base heights are computed functions fitted to observed test data.

**EM-1.** Curve fit to DNAF-1 calculations.

## 4.2 PARTICLE DISTRIBUTIONS.

The dust raised by a detonation is composed of individual particles ranging in size from fractions of microns to centimeters, or tens of centimeters for a subsurface burst. The particle size determines the speed of particle fall, which relates to the time after burst it reaches the ground and the distance it could move in that time. Linear functions of radius; normal, lognormal and log-log functions; power law functions; or various combinations such as Bakers recent bimodal distribution of two lognormal distributions (Reference 41), have all been suggested for use.

The distribution of particle sizes and the distribution of activity on the particles is considered to be the same in some codes but are a different distribution in others. If the activity is distributed uniformly throughout the particle, the distribution is a simple linear function of particle volume. If fractionation is considered to occur, the more volatile fission products do not condense as the particle is formed but rather condense and concentrate on the surface of already formed particles, and the distribution is a function of the surface area of the particle. If the total activity is to be considered a combination of both volatile and refractory elements, the partition of activity among the two will affect the radiation exposure calculations.

**DELFIC.** The default particle distribution is lognormal and based on ground-collected test data from shots Small Boy and ESS (one near surface and the other a shallow buried burst, both rather low yield). The lognormal median particle radius is ln(0.204), which was used to calculate a median particle radius of 123 microns, and the slope is ln(4).

**WSEG-10.** Based on grounded test data. Lognormal distribution of particle sizes, median size of 60 microns with a lognormal slope of ln(2). (However, see Section 4.3). The code treats mass and radioactivity content identically; thus, if 70 percent of the mass is deposited then 70 percent of the activity is also deposited.

**SEER3.** The size-mass distribution is used to apportion activity. Norment (Reference 42) contends that this produces a strong bias toward large particles with the effect of a disproportionately large amount of the activity assigned to large particles that ground close to the burst point. The particle population is divided into 25 different size groups. A log-log distribution for particles less than 100 microns in diameter and a lognormal distribution for larger particles is used. The resulting mix has been reported to be much like the Baker bimodal distribution (Reference 43).

**DNAF-1, EM-1.** Calculated from DELFIC results for an activity weighted average over all particle sizes. A standard lognormal median diameter of ln(0.40) microns and a slope of ln(4) was used to calculate particle sizes over a range of yields. The resulting average median diameter over all yields, 229 microns, is used in DNAF-1 and the EM-1 values are calculated from it.

## 4.3 FALL MECHANICS.

Important elements of fall mechanics are the size, shape, and density of the particles and the algorithms used to calculate their fall rate. A particle from a stabilized cloud will be transported by winds until it reaches the ground. Particle fall times are required so that the distance and direction traveled can be calculated. The particles are so small that they are assumed to always fall at terminal velocities, disregarding the negligible time required to accelerate to that velocity. Usually Stokes Law (for particles less than 10 microns) and the Davies solution using the Reynolds number (for particles greater than 10 microns) are used for fall rate determination, although some older codes used other methods. All codes consider the particle to be spherical, although test data shows both spherical and irregular shapes. Unless otherwise noted the default particle density used by all the codes considered here is 2.6 g/cc.

**DELFIC.** Stokes-Davies-Beard equations used for fall rate. Density of 2.6 g/cc is default, but can be specified by the user.

**WSEG-10.** Since the function g(t), representing the fraction of cloud activity deposited on the ground per unit time, was derived empirically, the model is entirely independent of assumptions regarding particle sizes or settling rates.

**SEER3.** Does not calculate the fall time for the different sized particles starting at different heights. Rather, the code contains 25 look up tables, one for each size group. Each table contains the time to fall from an initial height to the ground, with the initial height ranging from 500 to 40,000 meters, in 500 meter increments. Davies equations are used for fall rates.

**DNAF-1, EM-1.** Computed with DELFIC using the 1976 U.S. Standard Atmosphere. The calculations tracked about 100 size classes, 200 cloud layers and 20,000 fallout parcels to develop fall rate algorithms.

## 4.4 TOTAL ACTIVITY AND ACTIVITY TO DOSE RATE CONVERSION.

The fission products produce about 450 MCi of gamma radiation per kiloton of fission yield at one hour after detonation (H+1; one gamma radiation Ci equals an emission rate of $3.7x10^{10}$ gamma emissions per second) but can vary by about three percent depending on the fissile material and the fissioning neutron energy. The value 550 gamma MCi/KT, which compares the fission-produced gamma field to an equivalent monoenergetic source with an energy equal to the average fission product photon energy at one hour, is often used, especially in the older codes.

Exposure rate and dose rate are usually of greater concern than activity. The conversion is handled differently by the codes depending on whether airborne or ground-deposited activity is being calculated. For airborne activity, the detector is considered to be within the cloud, away from any ground source. The photon energy from each fission product and the mass attenuation coefficient of air and buildup factor to account for radiation scattering, along with the cloud volume, can be used to calculate the exposure. A simplification uses the average energy at H+1 hour (0.7 MeV) rather than summing the calculation of each radionuclide. The calculation reduces to a constant times the activity density at the detector divided by the air density at that altitude. For conversion of ground-deposited activity, the detector is assumed to be one meter above the surface.[3] The dose or exposure rate can be calculated as a constant times the activity per unit area, with the constant having units of roentgens-area per hour-unit activity.[4] This constant is often termed a "normalization" or "source normalization" or "K-factor" and is used by some codes to relate the activity to exposure. The K-factor relates the radiation intensity at H+1 hours after fission to the fraction of the total bomb produced activity per unit area measured one meter above a uniformly contaminated plane. In codes that model or at least acknowledge the existence of fractionation, the K-factor is meaningless.

**DELFIC.** Rigorous calculation of total activity at H+1 hour using decay chain data. The effects of fractionation are considered. An estimate of the refractory/volatility ratio is derived from decay-chain by decay-chain analysis of the fission products. By this estimate, about two thirds of the activity is in the form of refractory isotopes and is distributed by particle volume, the other third comes from volatile precursors and is distributed as a function of particle surface area.

**WSEG-10.** A K-factor of about 5180 (R-$km^2$)/(hr-KT) is used.

**SEER3.** No attempt is made to conserve activity. The result will be an overprediction of activity. The model predicts values for H+1 hour, and for hourly increments thereafter. A K-factor of 7770 (R-km$^2$)/(hr-KT) is used. There is evidence that the grid size selected for contour display affects the apparent K-factor.

**DNAF-1.** A K-factor of 6973 (R-km$^2$)/(hr-KT) is used.

## 4.5 DECAY.

Calculation of decay is an important parameter needed to reduce the activity calculations to a common time, or conversely to calculate the exposure at any time. Each fission fragment initiates a decay chain that can contain a number of radioactive nuclides before reaching stability. Codes handle decay in one of three ways. First, a code can model an initial distribution of fission products for a given weapon and track the subsequent decay chains in order to determine the total activity at any given time. Second, a code can use a single exponential value to represent the decay. Finally a code can use various exponential values, with each covering a different time after detonation. The third method is not presently used. The most popular single exponential is the Way-Wigner formulation (Reference 26) ; its basic form is $A_1 = A_0 t^{-1.2}$. Unfortunately, this equation was derived for beta rather than gamma decay and leads to considerable error when the radioactivity is calculated for times other than H+1 hours. The exponents of the full decay chain calculation vary with time from about -0.9 to more than -2.5, reflecting the changing abundance of the decay products and their energies over that time period.

**DELFIC.** Calculates and sums the complete decay chain.

**WSEG-10.** Uses $t^{-1.2}$.

**SEER3.** Uses $t^{-1.2}$, except near ground zero where an algorithm for soil activation is used.

**DNAF-1.** Uses $t^{-1.2}$.

**EM-1.** Uses an exponential function derived from the DELFIC calculated value and is felt to better represent fractionated fallout (Reference 44). This function, $t^{-1.26}$, fits DELFIC-generated data to within 10 percent between 15 minutes and 1,000 hours (Reference 45). An infinite dose calculated with this function will be about 25 percent less than one calculated using the Way-Wigner expression.

## 4.6 TRANSPORT.

As particles fall, whether the wafers of a disk thrower or the continuous vertical distribution of a smear code, they are transported by horizontal winds. These winds change with time and in geographic space as the cloud is transported. The local topography might have an effect on deposition, for example the altitude of the detonation and the altitude of particle grounding may not be the same, yet most codes assume a flat plane.

**DELFIC.** Each fallout parcel and subparcel is defined by the following: horizontal space coordinates of the parcel center, cloud base height, stabilization time, vertical thickness, radius, mass (or activity), mean particle diameter, and cloud volume. These data, along with input values of the vertical profiles of atmospheric pressure, temperature, humidity, density and viscosity, are used along with wind data to calculate cloud transport. Wind data are of one of three types: a single vertical profile, a sequence of single vertical profiles (used to update the wind field), or multiple profiles to account for variation of wind with geographic location. Turbulence may be specified by the user or calculated by the code. Particle settling speed is computed for each atmospheric stratum using the atmospheric properties for that layer for each particle size. The model produces a smoothed fallout pattern on the ground by transporting the disks, each representing one altitudinal section within the stabilized cloud, and grounding the top and base of the disk to separate impact points using the selected wind field. The end result of utilizing separate impact points for the top and base sections is calculated by the code as a bivariate Gaussian function to obtain distribution of fallout particles over the ground plane. Vertical wind shear during transport of the disks is converted into an ellipsoidal deposition function at the ground. Fallout pattern parameters are computed by summing the contributions from overlapping disk elements at any map point. Topography can be considered by the code.

**WSEG-10.** Uses a course wind resolution scheme. Monthly or seasonal averaged winds for five atmospheric layers are used. There is no cross fallout axis component of the winds.

**KDFOC2.** Uses horizontal wind speed and direction at each of 10 altitudes ranging from the surface to above the top of the debris cloud. Topography is not accounted for.

**SEER3.** Uses Global Weather Service wind data for seven altitude levels for points at every five degrees of latitude and longitude. The code interpolates midway between these points. Vertical wind shear is not accounted for; horizontal cloud growth of the moving cloud is modeled by increasing the size of the disks. Topography is not accounted for.

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**Notes**

1 Freiling's radial distribution model (see Appendix for reference) categorizes a nuclide as volatile if its boiling point is less than the solidification temperature of the soil particles and refractory if its boiling point is greater than the solidification temperature.

2 Three levels of sophistication are available. The first uses rigorous calculations that sum contributions of all nuclides in each decay chain. The second uses a rigorous calculation for the first hour, then $t^{-1.26}$ for subsequent times. The third is for pure airbursts and particle distributions are specified in terms of size-activity fraction, K-factors and use of the $t^{-1.26}$ decay factor.

3 Older conversions used three feet rather than one meter.

4 The roentgen, R, is the unit most commonly used by the codes to measure exposure. It is defined in terms of ions produced per unit mass of exposed material. The rad is the usual unit of radiation dose, where dose is the amount of radiation energy absorbed per unit mass. One rad is equal to the absorption of 0.01 Joule of absorbed energy per kg. The SI unit of radiation dose is the Gray, Gy, which is equal to one J/kg or 100 rad. For all practical purposes in fallout studies, one R of gamma radiation is taken to be equal to one rad.

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Portable Electronic Plotters: Dropsy (Sandia), AN/GMQ-18 (NBS/AEC), AN/GMQ-21 (Ford Inst.Co)

Operations Analysis Models: WSEG-10 (DoD), RAND-Surface Burst (RAND Corp.), DIA (DIA), NREC (DoD), Tech Ops/TOR (DNA), CDRP (Office of Civil Defense)

Physical Processes Models: NRDL-D (USNRDL), Miller-Anderson (USNRDL), Ford-T (Ford Inst. Co), LRL-b (LRL), LRL-h (LRL).

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